SANTOS: A DIGITAL HUMAN IN THE MAKING

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ABSTRACT
This paper presents the new developments of the next generation of the digital human Santos. The new features include (1) a 211-degree-of-freedom realistic skeletal model with deformable skin; (2) advances in a new method for dynamic motion prediction, called *predictive dynamics*; (3) advances in strength and fatigue modeling; and (4) advances in virtual human clothing interaction simulation. With these new developments, Santos can simulate posture and motion with higher accuracy, predict realistic cloth interaction, consider strength and fatigue factors in predictive dynamics, and facilitate improved and more efficient product design. In addition to providing new developments with various aspects of human modeling, this paper also highlights two high-level approaches to human modeling. First, predictive human modeling is addressed on the joint level, as opposed to the muscle level. This is especially novel with respect to strength and fatigue. Secondly, all aspects of human modeling either affect or are affected by motion prediction; predicting motion on the joint level is the core of the comprehensive human model. Ultimately, Santos can be deployed in different fields to serve various customers.

KEY WORDS
Digital human; predictive dynamics; muscle strength; muscle fatigue; clothing modeling; skeletal model

1. Introduction

Digital human modeling is becoming increasingly important to today's designers and manufacturers. Determining human performance in terms of a workplace or a product before it exists ensures consistence with health and safety standards, accelerates time-to-market, increases productivity, and reduces design timeframe and associated costs.

Commercial human models available in the market are Jack®, Ramsis®, and Safework®. Jack enables users to position biomechanically accurate digital humans of various sizes in virtual environments, assign them tasks, and analyze their performance. Ramsis specifically targets the automobile industries. The core capabilities of this software are the realistic display of international anthropometric data and the efficient analysis of ergonomic questions concerning sight, maximum force, reachability, and comfort. Safework structures multiple human modeling systems to facilitate detailed investigation into human-centered design issues. Other research and development digital human models include SAMMIE developed by Porter et al. (1999), the Boeing Human Modeling System (Rice, 2004), and Dhaiba (Mochimaru et al., 2006). However, all of these human models are based on experimental data.

To overcome the deficiencies of the current models, we are developing a new generation of digital human, Santos. This model is based on optimization techniques instead of prerecorded data. Consequently, it provides a tool for studying how and why humans move as they do. However, the human-body system is truly multi-scale, and any effort to model humans and their limitations must be multi-disciplinary. Consequently, Santos involves a variety of research and development projects. These include (1) skeletal modeling; (2) predictive dynamics; (3) clothing modeling; (4) strength and fatigue modeling; (5) physiology modeling; (6) an advanced hand modeling package; (7) posture prediction with multi end-effectors and real-time inverse kinematics (IK); and (8) muscle wrapping and muscle-force determination. In our previous reports (Abdel-Malek et al., 2006a; Abdel-Malek et al., 2006b; Kim et al., 2006; Man et al., 2006 Marler, 2005; Patrick, 2005; Yang et al., 2005; Yang et al., 2006a; Yang et al., 2006b) we demonstrated these capabilities. In this paper, we report on new developments with the skeletal model, strength and fatigue modeling, human-clothing interaction modeling, and predictive dynamics. This paper also discusses how the various components of human modeling are coupled together. One of the key elements of enabling this coupling is viewing predictive capabilities at the joint level rather than muscle level or spatial (Cartesian points) level. This is especially helpful with modeling strength and fatigue, and relating such models to motion prediction.

2. New Skinned Skeletal Avatar

This section discusses the newly developed skinned skeletal avatar. It consists of skeleton and skin.

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2.1 Skeleton

A potential restriction with any whole-body human model is the fidelity of the underlying musculoskeletal system. Consequently, a new system has been developed for Santos that mimics an actual human skeleton, providing the highest possible fidelity with respect to the number of degrees of freedom. The original kinematic skeleton used to predict gross human posture and motion in 2003 was dictated by the preliminary mathematical predictive models that had already been developed. The requirements of the predictive models at that time specified a total of 15 degrees of freedom (DOFs). While not biomechanically accurate, this kinematic skeleton led to important advancements in the predictive mathematical models for gross human posture and motion. Over time, additional DOFs were added to incorporate the left arm, neck, and legs, as well as to address visually unsatisfying postures and motion during extreme reaches resulting in a kinematic skeleton with 109 DOFs. While still not biomechanically correct, this kinematic skeleton has been used to produce highly realistic gross human motion and posture for the past two years.

Recent efforts at VSR required a more biomechanically accurate approach. Specific areas of interest include a more realistic representation of wrist pronation and supination; a shoulder model that addresses coupling of the clavicle, scapula, and humerus; and joints in the kinematic spine that coincide with significant anatomical landmarks. While it is obvious why a significant increase in kinematic skeleton complexity would require changes in the predictive models, an understanding of how a polygonal mesh (or skin) for any given avatar is prepared is required to better understand the cost of this process

The process of assigning groups of vertices of a polygonal mesh to a hierarchical joint structure so that the polygonal mesh behaves as if it had the material properties of human skin is well defined and is commonly referred to as “skinning” or “rigging” in the world of 3D computer animation. It begins with ensuring that the topology of the polygonal mesh (or skin) is optimized for human-like movement by arranging the polygons in a way that reflects how the underlying musculature expands and contracts around each of the joints. Once the skin has been optimized, a hierarchical joint structure (kinematic skeleton) representing all the joints must be developed and is shown in Fig. 1.

2.2 Skin

After the kinematic skeleton has been built, all the vertices in the polygonal mesh must be bound to the appropriate joints in the kinematic skeleton. This requires several weeks of dedicated time by a highly skilled 3D artist so it is important to avoid rigging until it is certain that the kinematic skeleton is correct (Fig. 2). However, the bones of a 3D skeleton do not bend or stretch which minimizes the rigging requirements to simply grouping entire bones to the appropriate nodes of the kinematic skeleton. This provided valuable visual feedback as the new kinematic skeleton was developed and tested without the expense of rigging avatars. Upon completion of the new kinematic skeleton, it was clear that the 3D skeleton model would provide a useful aid in ensuring that the locations of the kinematic joints for each avatar were anatomically correct as shown in Fig. 3.

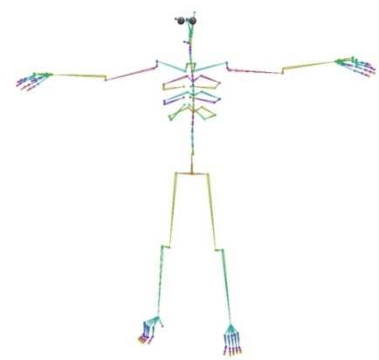


Fig. 1 Kinematic skeleton

The benefits of the new kinematic skeleton are; (1) the locations of the joints are based on bony landmarks of a 3D human skeleton derived from CT scan data; (2) every skeletal articulation is now accounted for, allowing for maximum extensibility in future research; and (3) this biomechanically correct skeleton now allows the mathematical models for predicting posture and motion to include deeper biomechanical factors, such as individual muscle forces and fatigue. It should be noted here that while this 3D skeletal model is not accurate enough to identify bone rugosity, it is accurate enough to identify significant anatomical landmarks.

(a) (b)

Fig. 2 Skin rigging: (a) Automatic rigging; (b) manual rigging

Anatomy experts were consulted to visually confirm that the location of the 3D skeleton within the mesh was reasonable before rigging, which is shown in Fig. 4.

Given this foundation for the human model, the next step is to model how the human moves. This is done using a new approach to dynamic motion prediction, called *predictive dynamics*.

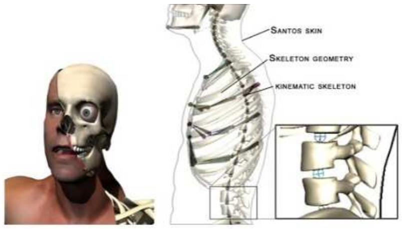


Fig. 3 A 3D model of a human skeleton used to identify anatomically correct locations for the kinematic joints

Fig. 4 New skinned kinematic model

3. Advances in Predictive Dynamics

Predictive dynamics (Kim et al., 2005; Kim et al., 2006) is a novel approach for predicting and simulating human motion. This optimization-based approach avoids solving typical differential algebraic equations (or ordinary differential equations) in order to create the resulting simulations for highly redundant systems. Detailed and anatomically correct joint-based full-body human models with high degrees of freedom can thus be used to create more realistic simulation of tasks with relatively less computation. Various tasks like walking (Xiang et al., 2007) and running (Chung et al., 2007) have been simulated using this approach. In this paper, we present the general formulation and examples such as stair climbing, throwing, and box lifting.

3.1 Optimization formulation

The problem statement for each of the dynamic tasks presented in this paper can be stated as follows: "Given task-based parameters, human anthropometry, segment inertial properties, physical joint motion and actuation limits, and desired time for completion, generate visually appealing and dynamically consistent task simulations that minimize dynamic effort." Such a problem statement lends itself to an optimization formulation, various components (design variables, performance measure, and constraints) of which are discussed below.

Design Variables

Joint angle profiles, $q_i(t)$, are approximated as linear combinations of cubic B-spline basis functions. Thus, the control points representing the B-splines are the design variables for the optimization problem. Corresponding joint angle, velocity, and acceleration values are calculated at each iteration, from these control point values.

Performance Measure

The goal of the optimization process is to reduce the dynamic effort at each joint. The performance measure (or objective function) is, therefore, to minimize the sum of the torque square for all joints over the simulation time as follows:

$$f(\mathbf{q}) = \int_{t=0}^{T} \sum_{i=1}^{ndof} \tau_i^2(\mathbf{q})\,dt$$

where *ndof* is the total number of joints of the human model, τ_i is the actuator torque of the i^{th} joint, and T is the total simulation time. Joint actuation torques are calculated using a recursive Euler-Largrangian formulation as a function of joint angles, velocities, and accelerations.

Constraints

Several physics-based and task-based constraints have been employed to predict the motions for various tasks. The physics-based constraints that are common for all tasks are joint angle limits, torque limits, no ground penetration, dynamic stability, and self-avoidance that ensures that different segments of the digital human do not penetrate each other (Xiang et al., 2007).

3.2 Tasks

i. Stair climbing

Prediction and subsequent simulation of the stair-climbing task requires specification of additional parameters like step length and step height. Additional (task-based) constraints imposed on the optimization problem are described below:

- *Symmetry Conditions*: One of the assumptions in predicting stairs climbing motion is symmetric and cyclic motion. Hence, to avoid any discontinuities of the joint angle profile for continuous motion, the initial and final postures of a step being simulated should satisfy the symmetry condition.
- *Foot Strike Position*: Foot strike position is also a function of step length and step height. The distance between the foot strike position on the staircase and the contacting points on the foot should be zero at contact.
- *Soft Impact*: The impact created when the foot lands on the ground must be minimized in order to reduce the loss of energy. This constraint has been imposed as zero velocity of contacting points.

Fig. 5 shows sequential snapshots of Santos climbing stairs. The motion appears visually realistic. However, in absence of any collision detection strategy, Santos' leg penetrates the stairs as seen in the first and last snapshots in the second row.

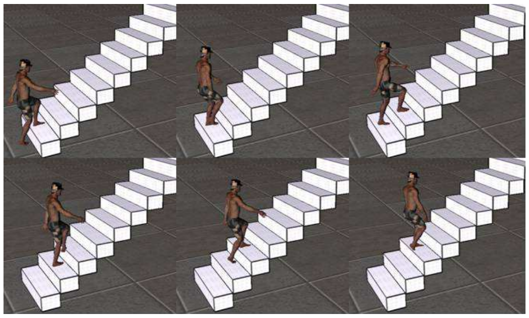


Fig. 5 Sequential snapshots of Santos walking up a staircase

ii. Throwing

Additional task-based parameters like mass of the object to be thrown and target location must be specified to simulate the highly redundant throwing problem. Some of the task-based constraints, as discussed below, are used to reduce the redundancy of the problem.

- *Initial posture*: The initial posture of the digital human is given by the user. Depending on the task requirement, all or some of the joint variables can be assigned. We also assume that the motion starts from a static pose.
- *Feet positions and orientations*: The global coordinates and the angles about the global Z axis for both feet are assigned by the user. The foot point coordinates are constrained accordingly.
- *Parabolic projectile equation*: For the object to hit the target point, the release position, release velocity, and flight time must satisfy the projectile equation.
- *Hand release orientation*: At the release point, the direction of the palm should be the same as the direction of the release velocity.
- *Overhand throw*: As part of the overhand requirement, the global *y* component of the right hand velocity should be always positive.
- *Visual perception*: This constraint requires that the target point should exist within the visual field of the human. The hand position at the release point should also be located within reasonable visual range so that the human can use the perception to control the release movement.

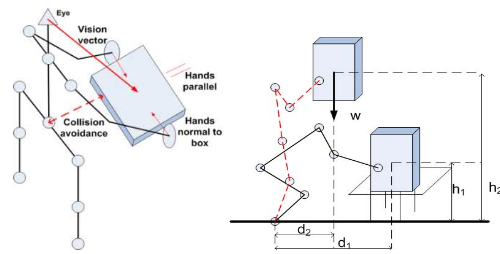
Fig. 6 shows sequential snapshots of Santos throwing an object. Visually, the motion appears close to the baseball pitching motion. The resulting simulation shows that Santos tries to generate torques with the help of the full upper body to create the force necessary for throwing.

Fig. 6 Snapshots of Santos throwing an object

iii. Box lifting formulations

Simulation of the box-lifting task requires the specification of initial and final box locations as well as the weight of the box to be lifted. Several task-based constraints as described below are implemented in this work to satisfy boundary conditions throughout the lifting process (See Fig. 7(a)):

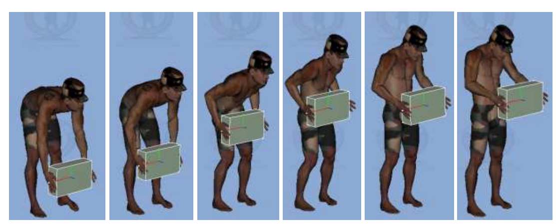
- *Hand orientation*: Two hands are normal to the box to facilitate the grasping postures for hands.
- *Vision*: The vision constraint aligns the vision vector towards the box center.
- *Collision avoidance*: The collision-avoidance constraint is used to keep the box from penetrating the body.



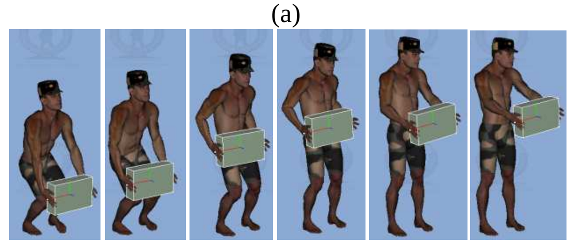
(a) (b)

Fig. 7 Box-lifting task (a) Hand orientation, vision, and collision-avoidance constraints (b) Input parameters

The lifting task is to lift the box from the initial location to the final location. The initial location is h_1 high from the ground and d_1 away from the feet; the final location is h_2 high from ground and d_2 away from the feet, as depicted in Fig. 7(b). The location parameters and box weight (w) are input parameters for the task.



(a)



(b)

Fig. 8 Sequential snapshots of Santos moving a 10-lb box from a lower shelf to a higher shelf (a) without any torque limits on the spine, and (b) with torque limit on the spine (time progression from left to right)

Fig. 8 shows the results of a box-lifting prediction for lifting a 10-lb box from a lower shelf to a higher shelf. The sequential snapshots in Fig. 8(a) show that much of the dynamic effort is contributed by the spine. However, when torque limits are applied to the whole body, the

resulting simulation in Fig. 8(b) shows contributions from knee and hip torque rather than spine torque to lift the box.

3.3 Integration with Other Components of Human Modeling

Motion prediction is the keystone of the Santos human model; other components either affect motion or draw on the output from motion prediction, as shown in Fig. 9**.** When metabolic energy is used as a performance measure with predictive dynamics, then various physiological indices (heart rate, oxygen consumption, body temperature, etc.) can be determined (Mathai, 2005). Joint torque, joint angles, and body position from predictive dynamics can be used to conduct ergonomic analysis. Actuation joint torques from predictive dynamics can be used to determine muscle force (Patrick, 2005), which can then be used to calculate muscle stress and displacement (Zhou and Lu, 2005).

The following two sections will describe in detail how clothing affects motion, and how strength and fatigue models can be linked to motion. Ultimately, we are able to indicate not just when Santos can or cannot complete a task, but how Santos alters his performance based on strength and fatigue, or various clothing designs.

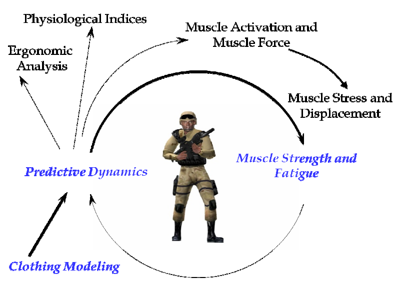


Fig. 9 Multiple components of human modeling

4. Muscle Strength and Fatigue

Muscle modeling includes muscle strength and muscle fatigue. In this section we present the advances in muscle modeling.

4.1 Muscle/ Joint Strength

In vivo muscle force is a highly nonlinear phenomenon that is dependent on factors such as muscle length, contraction velocity, and past contractile history (e.g., fatigue). While muscle force has been modeled as a linear system, linear representations are not as accurate as more complex nonlinear models (Frey Law and Shields, 2006). Force decays nonlinearly with increasing velocity (Hill, 1938). Active muscle force varies with muscle length, due to varying overlap of the force-producing filaments (i.e., actin and myosin), and stretching of structural proteins at long muscle lengths. It is not a simple transformation to apply these principles from the single muscle level to the joint level due to multiple synergistic muscles acting at a joint and the varying muscle moment arms with joint angle. Our approach to modeling joint strength inherently includes each of these nonlinearities.

We are experimentally measuring joint peak torque at several angles through the normal range of motion and at several angular velocities (e.g., 0 - 300°/sec) for 6 major body joints. These data are used to create 3D surfaces, with peak torque (strength) as a function of joint position and angular velocity (Laake, 2007). While previous authors have reported similar 3D representations of joint strength (Anderson et al., 2007), no one has developed a normative database to use for digital human modeling. This database will allow us to represent human strength capability as percentiles, similar to how anthropometry is represented, e.g., 5^{th}, 25^{th}, 50^{th}, 75^{th}, and 90^{th} %iles of human strength capability for men and women. Note that these population %iles are unrelated to anthropometric (height) percentiles, as tall individuals can be relatively weak or, conversely, short individuals relatively strong.

a. Incorporating Strength into Santos

Santos predicts the required joint torques (versus time), along with joint angle and velocity needed to accomplish a given dynamic task. If we plot the predicted joint torque versus joint angle and angular velocity at each point in time, we can assess the magnitude of the predicted joint torque relative to a population percentile's maximum capability (i.e., 50^{th} %ile male normative 3D surface). This provides a model of percent effort, where the closer the predicted task lies to the maximum surface, the more difficult a task becomes. This provides a unique methodology for a digital human to predict the perceived level of difficulty of a subtask, incorporating known muscle force determinants such as muscle length, moment arm, and shortening velocity into one simple process. To demonstrate this process, walking with and without a 40-lb backpack was modeled, with the resulting knee joint position, velocity, and torque predictions shown in Fig. 10 a-c. Fig. 10d plots this data relative to the 5^{th}-percentile male strength surface (knee flexion), showing that walking with a 40-lb backpack becomes nearly maximal intensity for the weakest 5% of males. Although not shown, this task is only moderately challenging for the 50^{th}-%ile strength male population, and easy without the backpack.

4.3 Muscle/ Joint Fatigue

As muscles fatigue, both maximum torque and velocity are impacted, e.g., it becomes increasingly more difficult to generate large joint torques and high movement velocities. Thus, we can use the 3D joint strength surfaces to represent fatigue by decaying them with repetitive or higher intensity activities. We have developed a model which predicts how a joint surface will decay over time, using a series of differential equations based on compartment and control theories (Xia and Frey Law, 2008). A single three-compartment model represents muscles involved at a joint in one of 3 states: active,

resting, or fatigued. Rate constants define the behavior of the transfer between the active and fatigued compartments; however, we use a proportional controller to define the transfer between resting and active states. The model determines how much of the resting muscle pool must be activated in order to match the predicted joint torques. The combined size of the resting and active pools determines the residual capacity of the system for use as a decay coefficient (values between 0 and 1) to decay the 3D strength surface. This can be used both as a feedback, post-processing mechanism, providing a means to measure “time to fatigue” when the task is no longer feasible without alterations in the predicted dynamics; and/or a feed-forward mechanism where the predicted dynamics can change as the available strength decreases. Most notably, we incorporate strength nonlinearities into or fatigue model by normalizing predicted dynamic joint torques by the corresponding peak 3D strength representation (% of maximum torque). Thus, the model targets this % max torque rather than a specific absolute muscle force or torque, as typically used by other models.

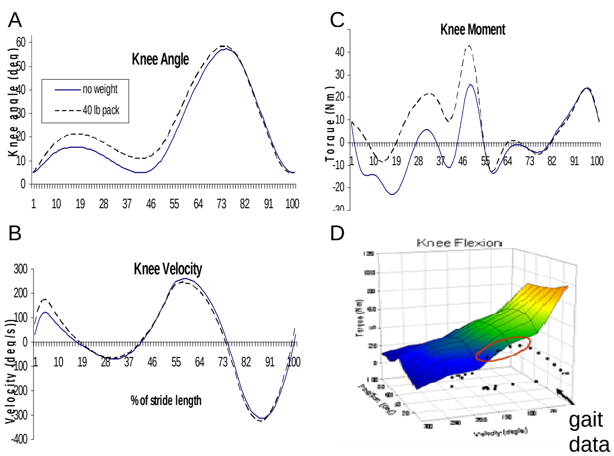


Fig. 10 Predicted gait dynamics: A) knee angle, B) velocity, and C) peak torque per stride length with and without a 40-lb backpack. D) The 40-lb gait data vs. the male 5^{th} %ile strength surface for knee flexion.

5. Human-Clothing Interaction Modeling

In the present framework, the clothing is modeled as flexible continuum shells draped onto an active piecewise rigid human body surface. The clothing model undergoes unilateral frictional contact with the moving human body model and exerts associated forces on the human body. These forces can then be used to calculate the energy necessary to move the clothing, which can be substantial with heavy protective suites. Here, we describe how a subject-specific human body surface driven by predictive dynamics is approximated with piecewise rigid mesh segments and how the clothing is draped onto the body surface. Although not the focus here, constitutive behavior of different clothing fabrics is an important aspect of clothing modeling (Swan et al., 2007).

The starting point for a virtual mannequin representing the anthropometry of a specific human subject is a laser body scan, which yields a polygonal mesh (Ashdown, 2007) involving hundreds of thousands of nodes and polygons. Such meshes are much finer than is necessary for clothing modeling, and indeed usage of such fine meshes would be too computationally expensive in clothing contact modeling. Accordingly, the body-surface mesh can be coarsened using commercial software tools (Fig. 11). Once a complete and coarsened body scan mesh is obtained, it is decomposed into an assemblage of individual meshes corresponding to limb or torso segments. The optimal decomposition of meshes into segments can itself be quite involved (see, e.g., Lien, 2006) but was done here (Fig. 11c) in an ad-hoc manner at the major joint locations using AutoCAD.

The individual body mesh segments are subjected to rigid body translations and rotations in time to approximate evolution of the body surface as the human subject performs physical tasks. Geometric inconsistencies will develop at the joints between the rigid body mesh segments (Fig. 12a), and since such gaps present a problem in clothing modeling, they are patched in the current framework using auxiliary spherical and ellipsoidal rigid mesh segments at each of the joints between body mesh segments (Fig. 12b).

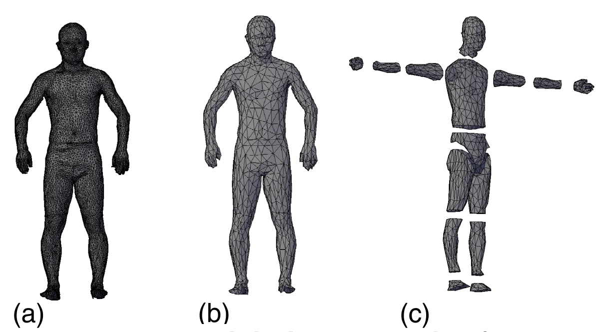


Fig.11. (a) Original body scan mesh of 230,000 polygons; (b) coarsened mesh of only1,700 polygons; and (c) coarsened mesh decomposed into segments.

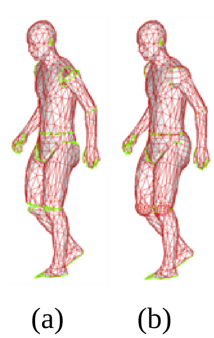


Fig. 12 (a) Virtual mannequin in action and developing gaps at the joints, specifically here at the left shoulder and right knee; (b) Virtual mannequin with rigid spherical and ellipsoidal joint segments that become exposed when the gaps would otherwise form between the rigid body mesh segments.

With a controllable piecewise rigid body surface for the mannequin in place, clothing models can be draped onto the mannequin. A number of different approaches have been taken to get the clothing model onto the human body. Two in particular are trying to simulate the actual

dressing process (Man and Swan, 2007; Volino and Magnenat-Thalmann, 2000) and trying to pre-position models of clothing patterns around models of the human body and then bring the patterns together and stitch them up at their seams (Groβ et al., 2003), essentially constructing the garment about the mannequin. Here, we try a different approach that involves two steps: (1) the clothing is statically pre-positioned over the mannequin without any concern for contact or penetration between the body and the clothing; and (2) once the clothing model is in place, contact mechanics (penetration detection and correction) are turned on to eliminate clothing penetrations of the body surface.

When pre-positioning the assembled clothing models about the body in a fixed posture, the objective is to bring the centroids of the clothing model edges (cuffs, waistline, necklines, etc.) into alignment with the corresponding body-segment edge centroids. This is achieved by using penalty forces that are significant when the clothing and body segment edge centroids are not coincident and are minimized as the clothing becomes properly positioned on the body. This pre-positioning problem is solved quasi-statically, leaving the clothing model properly positioned on the body in a gross sense, although with some significant clothing penetrations of the body (Fig. 13).

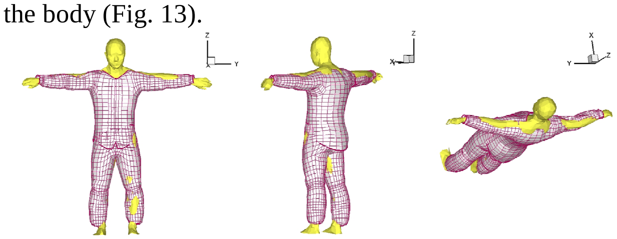


Fig. 13 Results of the clothing pre-position step where, without any concern for penetrations, the edge centroids of the garment models are brought into alignment with the edge segment centroids of the corresponding body segments; clothing penetration of the body is especially evident at the shoulders and tops of arms

In the second stage, explicit dynamic analysis of the clothing model is performed while gravity loading pulls downward on the clothing model, and explicit contact analysis as described by Man and Swan (2007) is utilized to remove starting penetrations and any other penetrations that develop. Virtually all of the initial clothing penetrations from the pre-positioning stage are eliminated in this phase of analysis (Fig. 14). From this stage, the mannequin can be activated based on joint-angle profiles from predictive dynamics, and the clothing model will respond accordingly via frictional contact interactions with the mannequin surface.

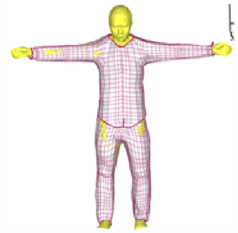


Fig. 14 Result of second stage analysis in which gravity loading is applied along with contact mechanics to remove initial clothing penetrations of the body

Conclusions

This paper presents new developments for the digital human Santos. These new capabilities include a high-fidelity skinned kinematic skeleton model with over two hundred DOFs, advances in muscle strength and fatigue modeling (working at the joint-space, incorporating 3D dynamic joint torque and the development of a new fatigue model), advances in cloth modeling (human and cloth interaction modeling), and advances in predictive dynamics (simulation for different tasks such as walking on stairs, throwing, and box lifting). In addition to these new developments, a variety of inter-related research efforts are ongoing: hand modeling, such as grasping and the development of hand comfort metrics; advanced posture prediction (whole-body posture with global translation and rotation DOFs) for the new skeletal model; development of a zone differentiation tool; predictive dynamics tasks such as kneeling, side walking, ladder climbing, and ingress/egress; further refinement of the polygonal topology to allow for facial expressions and blinking and refinement of the skin weighting to address any skin tearing issues we discover as we begin using the avatars with the new kinematic skeleton, and interface development.

This paper illustrates the necessity for multi-disciplinary work when modeling humans. In addition, as shown in Fig. 10, various research-and-development efforts must all link together, providing a comprehensive human model. The joint-based focus of our model helps facilitate this connectivity between various aspects of a virtual human.

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References

1. Abdel-Malek, K., Yang, J., Marler, T., Beck, S., Mathai, A., Patrick, A., and Arora, J. (2006a) "Towards a new generation of virtual humans," *International Journal of*

Human Factors Modelling and Simulation, Vol. 1, No. 1, pp. 2-39.

2. Abdel-Malek, K., Arora, J., Yang, J., Marler, T., Beck, S., Swan, C., Frey-Law, L., Mathai, A., Murphy, C., Rahmatalla, S., and Patrick, A., (2006b) "Santos: a physics-based digital human simulation environment," 50th Annual Meeting of the Human Factors and Ergonomics Society, San Francisco, CA, October 2006.
3. Anderson, D.E., Madigan, M.L., and Nussbaum, M. A. (2007) "Maximum voluntary joint torque as a function of joint angle and angular velocity: model development and application to the lower limb," *J Biomech*, Vol. 40, pp. 3105-13.
4. Ashdown, S. (2007), www.bodyscan.human.cornell.edu.
5. Chung, H.J., Xiang, Y., Mathai, A., Rahmatalla, S., Kim, J., Marler, T., Beck, S., Yang, J., Arora, J., and Abdel-Malek, K. (2007) "A robust numerical formulation for the prediction of human running," *Proceedings of SAE Digital Human Modeling for Design and Engineering*, June 12-14, 2007, Seattle, University of Washington, WA, USA.
6. Ding, J., Wexler, A.S., and Binder-Macleod, S. A. (2002) "A predictive fatigue model--II: predicting the effect of resting times on fatigue," *IEEE Transactions on Neural Systems & Rehabilitation Engineering*, Vol. 10, pp. 59-67.
7. Ding, J., Wexler, A. S., and Binder-Macleod, S. A. (2002) "A predictive fatigue model--I: predicting the effect of stimulation frequency and pattern on fatigue," *IEEE Transactions on Neural Systems & Rehabilitation Engineering*, Vol. 10, pp. 48-58.
8. Epstein, M. and Herzog, W. (1998) *Theoretical Models of Skeletal Muscle Biological and Mathematical Considerations*. New York: John Wiley & Sons.
9. Frey Law, L.A. and Shields, R.K. (2006) "Predicting human chronically paralyzed muscle force: a comparison of three mathematical models," *J Appl Physiol*, Vol. 100, pp. 1027-36.
10. Grob, C., Fuhrmann, A., and Luckas, V. (2003) "Pre-positioning of virtual clothing," Proc. 19th Spring Conference on Computer Graphics, ACM.
11. Hawkins, D. and Hull, M.L. (1993) "Muscle force as affected by fatigue: mathematical model and experimental verification," *J Biomech*, Vol. 26, pp. 1117-28.
12. Hill, V.A. (1938) "The heat of shortening and the dynamic constants of muscle," *Proceedings of the Royal Society of London B*, Vol. 126, pp. 136-195.
13. Kim, H.J., Horn, E., Arora, J., and Abdel-Malek, K. (2005) "An optimization-based methodology to predict digital human gait motion," *Proceedings of SAE Digital Human Modeling for Design and Engineering*, June14-16, 2005, Iowa City, IA, USA.
14. Kim, J., Abdel-Malek, K., Yang, J., and Marler, T. (2006) "Prediction and Analysis of Human Motion Dynamics Performing Various Tasks," *International Journal of Human Factors Modelling and Simulation*, Vol. 1, No. 1, pp. 69-94.
15. Laake, A., and Frey Law, L.A., "Modeling 3D knee torque surfaces for males and females," presented at American Society for Biomechanics, Palo Alto, CA, 2007.
16. Lieber, R.L. (1992) *Skeletal Muscle Structure and Function. Implications for Rehabilitation and Sports Medicine*. Baltimore, Maryland: Williams & Wilkins.
17. Lien, J-M (2006). *Approximate convex decomposition and its applications*, PhD Dissertation, Texas A&M University.
18. Man, X., Swan, C., and Rahmatalla, S. (2006), "A clothing modeling framework for uniform and armor system design," Modeling and Simulation for Military Applications. *Proceedings of the SPIE*, Vol. 6228.
19. Man, X., and Swan, C. C. (2008) "A mathematical modeling framework for analysis of functional clothing" Journal of Engineered Fibers and Fabrics, *in press.*
20. Mathai, A.J., (2005), "Towards physiological modeling in virtual humans," M.S. Thesis, The University of Iowa, Iowa City, IA.
21. Marler, R. T. (2005), "A study of multi-objective optimization methods for engineering applications," Ph.D. Dissertation, University of Iowa, Iowa City, IA.
22. Mochimaru, M., Kouchi, M., Miyata, N., Tada, M., Yoshida, Y., Aoki, K., Kawachi, K., and Motomura, Y. (2006) "Dhaiba: functional human models to represent variation of shape, motion and subjective assessment," Proc. SAE 2006 Digital Human Modeling for Design and Engineering Conference, pp.2006-01-2345, Jul., 2006.
23. Patrick, A. (2005) "Development of a 3D model of the human arm for real-time interaction and muscle activation prediction," MS Thesis, The University of Iowa, December 2005.
24. Porter, J.M., Case, K., and Freer, M.T., (1999) "Computer aided design and human models," in The Occupational Ergonomics Handbook, Karwowski, W., and Marras, W.S., Eds., Boca Raton, FL: CRC Press, 479-500.
25. Rice, S., (2004) Boeing human modeling system, in Working Postures and Movements Tools for Evaluation and Engineering, Delleman, N., Haslegrave, C.M., and Chaffin, D.B., CRC Press, 462-465.
26. Swan, C. C., Man, X., Yang, J., Rasmussen, M., and Williams, R. (2007). "Multiscale analysis for virtual prototyping and performance testing of protective fabrics," paper IMECE2007-43925 presented at ASME IMECE. Seattle, WA.
27. Volino, P., and Magnenat-Thalmann, N. (2000) Virtual Clothing, Theory and Practice. Springer.
28. Xia T and Frey Law L. (2008). Multiscale Approach to Muscle Fatigue Modeling. *Pacific Symposium on Biocomputation 2008*, Big Island, Hawaii, January 4-8, 2008.
29. Xiang, Y., Chung, H.J., Mathai, A., Rahmatalla, S., Kim, J., Marler, T., Beck, S., Yang, J., Arora, J., and Abdel-Malek, K. (2007) "Optimization-based dynamic human walking prediction," *Proceedings of SAE Digital Human Modeling for Design and Engineering*, June 12-14, 2007, Seattle, University of Washington, WA, USA.
30. Yang, J., Marler, T., Kim, H.J., Farrell, K., Mathai, A., Beck, S., Abdel-Malek, K., Arora, J., and Nebel, K. (2005) "Santos^{TM}: a new generation of virtual humans," *SAE 2005 World Congress*, Cobo Center, Detroit, Michigan, USA.
31. Yang, J., Marler, T., Beck, S., Kim, J., Wang, Q., Zhou, X., Pena Pitarch, E., Farrell, K., Patrick, A., Potratz, J., Abdel-Malek, K., Arora, J., and Nebel, K. (2006a), "New capabilities for the virtual-human Santos^{TM}," *SAE World Congress*, Cobo Center, Detroit, Michigan.
32. Yang, J., Pena Pitarch, E., Kim, J., and Abdel-Malek, K., (2006b), "Posture prediction and force/torque analysis for human hands," *Proceedings of SAE Digital Human Modeling for Design and Engineering*, July 4-6, 2006, Lyon, France.
33. Zhou, X. and Lu, J. (2005), "NURBS-based Galerkin method and application to skeletal muscle modeling," In Proceedings of the 2005 ACM Symposium on Solid and Physical Modeling. SPM '05. ACM Press, New York, NY, 71-78.